

Sources of sediment to the Great Barrier Reef World Heritage Area

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Abstract

To reduce sediment exports discharging to the Great Barrier Reef (GBR), it is essential to identify the sources of exported sediment. We used modelling of spatial sediment budgets (the SedNet model) to identify sources and deposition of sediment as it is transported through river networks. Catchments with high levels of land clearing, cattle grazing and cropping show the largest increases in sediment export compared with natural conditions. Hillslope erosion supplies 63% of sediment to the rivers. Gully erosion and riverbank erosion are lower sources of sediment at the GBR catchment scale, but they are important in some catchments. Overall, 70% of sediment exported from rivers comes from just 20% of the total catchment area, showing that much of the problem can be addressed in a relatively small area. This is a much more manageable problem than trying to reduce erosion across the entire GBR catchment. Areas of high contribution are all relatively close to the coast because of the high erosion and high sediment delivery potential.

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Keywords: Suspended sediment; Great Barrier Reef; Sediment budgets; Spatial modelling; GIS

1. Introduction

In the catchments adjacent to the Great Barrier Reef (GBR) widespread clearing of native vegetation and replacement with intensive cropping and grazing systems have increased erosion and river sediment exports to many times the natural amount (Furnas, 2003; McCulloch et al., 2003). Increased sediment exports threaten to degrade inner shelf reef and benthic ecosystems, particularly those of the central and southern GBR (Brodie, 2002; Furnas, 2003). The nearshore zone at most risk contains 438 coral reefs, 462 km² of seagrass beds, dugong habitats, supports important fisheries and contains significant tourism destinations (Brodie, 2002). Increased sediment exports can inhibit growth of shallow seagrass beds and inshore reefs in deposition areas

and increase eutrophication (Bell and Elmetri, 1995; Wolanski and Spagnol, 2000; Wolanski and Duke, 2002; Wolanski et al., 2003; Fabricius and De'ath, 2004). Mid and outer shelf reefs do not appear to be at high risk from increased terrestrial runoff (Devlin et al., 2003). The combined impact of runoff and other stresses, such as freshwater inundation, cyclones, crown-of-thorns starfish and high water temperatures, may cause devastating changes (Fabricius and De'ath, 2004).

While the precise impacts remain uncertain (Larcombe and Woolfe, 1999a,b), there is general agreement that inshore areas are under threat and that sediment exports need reducing now for the threat to be removed. In June 2001, the GBR Ministerial Council initiated a process to set water quality targets for the GBR World Heritage Area (GBRWHA). As a result of this process, the Great Barrier Reef Marine Park Authority (GBRMPA) published end-of-catchment targets for suspended sediment (SS), nitrogen and phosphorus, and targets

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for chlorophyll and sediment associated pollutants in the GBR lagoon (Brodie et al., 2001, 2003a). More recently, the federal and Queensland governments have developed a Reef Water Quality Protection Plan (RWQPP) to protect the Reef from land-based sources of pollution. The long-term target of the RWQPP is to halt and reverse the decline in water quality entering the Reef within 10 years (Anon, 2003).

The GBR catchment area is vast and diverse covering 423,000 km². The region includes large river basins with open, low energy floodplains draining inland Savannah grazing and cereal and cotton cropping lands. At the other extreme are small, high energy, coastal rivers draining wet tropic rain forest and sugar cane and horticulture croplands (Furnas, 2003). It is beyond current resources to systematically control erosion and sediment transport across the whole area, and we show in this paper that this is unnecessary. Thus, to prioritise rehabilitation efforts, we need techniques that identify the sub-catchments and erosion processes that contribute the bulk of the sediment. The variability of environments and land uses across the region make this a challenging task.

Monitoring of river sediment loads has revealed the scale of sediment export to the reef from some catchments (Furnas and Mitchell, 2001; Furnas, 2003). Sampling of the Normanby, Barron, Johnstone, Tully, Herbert, Burdekin and Fitzroy Rivers, was initiated in 1987 by the Australian Institute of Marine Science (AIMS). This monitoring provides the only actual measurements of sediment concentrations and load estimates. The expense and effort required mean that not all rivers are monitored and until now the monitoring has been limited to fixed-term funding, with little ongoing commitment. Rainfall and runoff vary greatly from year-to-year so the limited spatial and temporal scope of monitoring mean that some form of modelling is required to assess the patterns of export to the GBR, even if it is just extrapolation of monitoring data. More importantly, modelling is required to interpret the patterns of sediment sources within catchments.

A number of models have been developed to estimate sediment exports to the GBR. The models and data supporting them have grown in sophistication and reliability over time. Sediment exports have been calculated from the estimated accumulation of sediment in the coastal sediment wedge (Belperio, 1983), weighted discharge–transport relationships derived from a small number of rivers (Neil and Yu, 1996) and simple models of land use, runoff and sediment delivery (Moss et al., 1992; Rayment and Neil, 1997). More recently, discharge–export relationships derived from the AIMS monitoring have been used to estimate sediment exports (Furnas and Mitchell, 2001; Brodie and Furnas, 2003; Furnas, 2003). These models extrapolate from gauged basins to predict the pattern of export along all 35 river

basins using empirical relationships to factors such as discharge, land use, or catchment area. They all make implicit assumptions that conditions in monitored catchments can be applied to the unmonitored catchments. When tested as predictive models they typically have large residual errors that represent the additional environmental factors that control sediment transport in diverse environments. They do not address the source of the sediment within each of the river basins.

We take an alternative conceptual approach to modelling river basin sediment exports, which can also be used to predict the sources of sediment within each basin. This approach models spatially-distributed sediment budgets of the primary erosion and deposition processes. We map patterns of hillslope, gully, and riverbank erosion and sediment deposition on floodplains, riverbeds and in reservoirs across the GBR catchment, and use them to construct a mean annual mass balance for each link of the river network. Each of the erosion and deposition processes is mapped from the primary controlling environmental factors using empirical and conceptual models. The environmental factors include the effects of terrain, rainfall characteristics, soil properties, land use, and hydrology. The sediment budget model is called *SedNet* (*Sediment River Network Model*; Prosser et al., 2001b).

The guiding concept behind the budgets is that suspended sediment transport is supply limited. That is, the amount and pattern of mean annual suspended load is determined by the supply to rivers from erosion sources, as has been widely inferred from measured loads and concentrations (Olive and Walker, 1982; Williams, 1989). High rates of erosion will lead to high sediment concentrations and low rates will lead to low concentrations. The approach contrasts with hydrological modelling, based directly on gauging data, which typically assumes that sediment concentrations are constant between basins and can be extrapolated from one catchment to another, so that load is proportional to discharge. This implicitly assumes that suspended sediment transport is limited by transport capacity of the discharge not supply of sediment.

Field and geochemical tracer sediment budgets suggest that there are several sources of sediment contributing to coastal exports. Riverbank and gully erosion, accelerated by changes in land use, can be the predominant source of sediment across a range of environments (Wallbrink et al., 1998; Prosser et al., 2001b; Poesen et al., 2003). This is not always acknowledged in catchment erosion modelling which often focuses purely on soil erosion by surface wash processes. Comparisons of catchment erosion rates with river sediment loads (Walling, 1983) show that in large rivers much of the sediment is deposited on floodplains (Dunne et al., 1998), riverbeds (Trimble, 1981) and in reservoirs and does not contribute to coastal exports. Patterns of

deposition, like erosion, will vary strongly from one river reach to another and control the yield of sediment. Confined, high energy rivers will deliver sediment efficiently, while those with open, low energy channels and floodplains will store much sediment, stopping it from contributing further downstream.

Sediment budgets are widely used in geomorphology, but their use in spatial modelling is new. There are several advantages of using sediment budgets as a framework for spatial modelling. First, they provide a useful integrating framework for all the knowledge and environmental data relevant to sediment transport. In addition to spatial data, this can include river flow measurement, river surveys, erosion studies and water quality monitoring. Second, in a budget, all the inputs of sediment to a system must be balanced with any stores and losses from the system. This means that predictions from one part of the budget constrain and inform other parts. For example, an overprediction of hillslope erosion can be detected by abnormally high rates of floodplain deposition that it induces. Lastly, but most significantly, the spatially distributed approach of SedNet allows us to predict where in a catchment the exported sediment comes from and the dominant erosion processes in those places.

2. Methods

The spatially distributed sediment budgets were modelled using the SedNet suite of ARC/INFO scripts first developed and applied to the National Land and Water Resources Audit (NLWRA; Prosser et al., 2001b) using the principles outlined in Prosser et al. (2001a). Here we give a brief overview and outline the data sources used in this study. Full details of the methods and full mapped results are given in Brodie et al. (2003b).

SedNet divides the river network into river links, which are the basic calculation unit for the sediment budget. A link is a section of river or stream between adjacent stream junctions (or nodes; Fig. 1). Each link has an internal catchment area, that is, the land that drains directly into that link.

For each river link (i , Fig. 1) a mean annual mass balance (t/y) is calculated:

$$Y_i = T_i + H_i + G_i + B_i - D_i$$

where Y_i is the mean annual yield of sediment, T_i is tributary sediment input; H_i is hillslope erosion; G_i is gully erosion, B_i is riverbank erosion and D_i is net deposition on the floodplain and riverbed (or reservoir).

The model requires mapping of hillslope erosion and gully erosion in the landscape. The model itself calculates rates of riverbank erosion. These three sources are the sediment inputs into the river network.

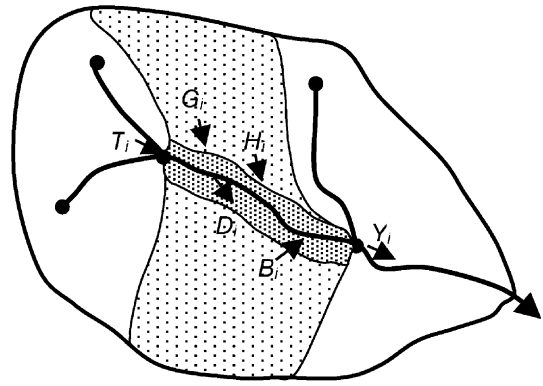


Fig. 1. Conceptual diagram of mean annual sediment budget (t/y) for one river link and its associated sub-catchment (light shade) and floodplain (dark shade). Budget terms are defined in the text.

2.1. Hillslope erosion

Mean annual hillslope erosion by surface wash and rill erosion processes was predicted using the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997). The RUSLE calculates mean annual soil loss (H , t/ha/y) as a product of six factors: rainfall erosivity (R), soil erodibility (K), hillslope length (L), hillslope gradient (S), vegetation cover and land use (C), and supporting practice (P):

$$H = RKLSCP$$

Rainfall erosivity and soil erodibility data were obtained from the NLWRA dataset (see Lu et al., 2001, 2003). Hillslope length and gradient data were derived as for the NLWRA (Gallant, 2001) using the national 9 second digital elevation model (DEM; AUSLIG, 2000) or high resolution DEMs where available. Ground cover was derived from land use mapping to generate a typical C factor for each cover type, guided by a review of observed soil erosion rates across Australia (Lu et al., 2003). Due to lack of spatial data on contour bank locations and other structures, the supporting practice factor was omitted.

Natural hillslope erosion rates were also calculated using the same procedure. While the RUSLE was formulated for agricultural lands, surface wash erosion processes do occur under natural vegetation cover in the wet tropics and the results can be roughly calibrated by fitting the vegetation cover factor to match observed rates of erosion. Natural vegetation cover was identified from the National Vegetation Information System (NLWRA, 2001) and assigned C factors guided by measured erosion rates reviewed by Lu et al. (2003).

A hillslope sediment delivery ratio (HSDR) was used to represent the proportion of hillslope erosion that reaches streams. This is the most uncertain term in the suspended sediment budget. A HSDR value of

10% produced results consistent with measured sediment loads, the dominance of channel over hillslope erosion in some areas (Wallbrink et al., 1998) and observed floodplain deposition rates (Prosser et al., 2001a).

2.2. Gully and riverbank erosion

Gully erosion was derived from the NLWRA gully erosion database (Hughes et al., 2001). The NLWRA gully density model was constructed by explaining the variability in gully density (km/km²), mapped from aerial photographs, using various environmental variables such as land use, soil texture, geology, relief and climatic indices in a geostatistical model (Hughes et al., 2001). Gully density was converted to a mean annual rate of erosion using typical values for gully age (100 y) and cross sectional area (10 m²) to produce the average sediment yield required to excavate a gully. The typical age and cross-section are based on field experience and published research e.g. Prosser and Winchester (1996). Gullies are new incised channels resulting from vegetation disturbance so the natural sediment budget assumed no sediment supply from gullies.

Riverbank erosion was estimated from a conceptual relationship based on limited data (Hughes and Prosser, 2003). It is assumed that the potential bank erosion rate is proportional to stream power but that the actual rate of erosion is reduced by riparian vegetation and the proportion of non-alluvial material in the banks, mapped from floodplain width. Riparian vegetation cover data was obtained from the State of the Rivers (DNR, 1996–1999) or the Australian Land Cover Change Project (Barson et al., 2000). Natural bank erosion was predicted from the same relationship using 95% riparian cover.

2.3. River sediment loads

Sediment sources are divided into separate budgets for suspended and bedload transport, reflecting the separate transport processes. Hillslope and half of gully and riverbank erosion are the inputs to the suspended load budget. The remaining gully and riverbank erosion contribute to the bedload budget. This separation is based upon observations from detailed field based sediment budgets (e.g. Dietrich and Dunne, 1978) and from particle size analysis of bank sediments which typically contain 50% of coarse sand and larger particles.

For each link suspended load can be lost to floodplain or reservoir deposition. There is no net suspended sediment deposition on riverbeds. Floodplain deposition (D_x ; t/y) was predicted from settling theory and water residence time on floodplains using inputs of floodplain width, mapped from the DEM, and analysis of time series of flood discharges.

$$D_x = \frac{Q_{fx}}{Q_x} I_x \left(1 - e^{-\left(\frac{v A_{fx}}{Q_{fx}}\right)} \right)$$

where Q_x is total discharge (m³/s); Q_{fx} is floodplain discharge (m³/s); I_x is the incoming sediment; v is the settling velocity of suspended sediment (m/s); and A_{fx} is the floodplain area (m²). Settling velocities of sediment were based on silt-sized sediment. Reservoir deposition was predicted using modifications of the Brune Rule (see Prosser et al., 2001b). The Brune Rule is an empirical relationship that uses mean annual flow and reservoir volume as surrogate indicators of average residence time of floods in the reservoir. Nearly all flood flows occur in summer in the GBR catchments, so we doubled annual flow rates for the calculation of reservoir deposition to represent this lower average residence time, and to avoid overestimating deposition.

Bedload budgets are not reported in this paper as they are of little consequence to the marine environment, with the bedload export making up approximately 10% or less of total sediment export. The vast majority of bedload is stored as sheets of sand and gravel on riverbeds.

2.4. Hydrology

The model requires various hydrological parameters for each river link, including bankfull discharge, median flood discharge and mean annual flow. These parameters are obtained at each gauging station from time series of daily flows. The resultant values are extrapolated to ungauged river links using multiple regression relationships with catchment area and rainfall. The techniques consequently take account of the highly seasonal flows and the highly variable peak discharges that transport most of the sediment.

3. Results and discussion

3.1. Sediment sources

The predicted mean annual supply of sediment to streams is shown in Table 1. Hillslope erosion (sheet-wash and rill erosion on sloping land) is the dominant process, supplying 63% of sediment to the rivers. The pattern of hillslope erosion estimated by the RUSLE is shown in Fig. 2b. Most of the areas of land with high hillslope loss rates (>10 t/ha/y) are on relatively steep sloping crop and grazing land within 100 km of the coast, where high rainfall erosivity increases the erosion hazard. Inland areas, of generally lower slope and low rainfall erosivity have hillslope loss rates of <5 t/ha/y. Areas having a low erosion rate (<2.5 t/ha/y) occupy

Table 1

Components of the sediment budget for the GBR catchment predicted by the SedNet model

Sediment budget item	Mean annual rate (kt/y)
Delivery from hillslope erosion	24900
Gully erosion rate	11200
Riverbank erosion rate	3300
<i>Total sediment supply</i>	<i>39400</i>
Total suspended sediment stored	17000
Total bed sediment stored	6800
Sediment export from rivers to estuaries	15600
<i>Total losses</i>	<i>39400</i>

50% of the catchment area, while areas with a high erosion rate (>10 t/ha/y) occupy just 14% of the total catchment area. These values represent local movement of soil on hillslopes and it is important to realise that only about 10% of this eroded soil finds its way to streams.

Some places such as steep slopes in the wet tropics have naturally high rates of hillslope erosion so not all areas of high erosion will be of greatest management concern. Comparison with predicted hillslope erosion rates under natural vegetation cover, suggest that

current rates in grazed and cropped areas are accelerated by at least five times.

Gully erosion is also a significant source of sediment, but is localised within a few catchments such as parts of the Burdekin and Fitzroy catchments (Fig. 2c, see Fig. 2a for catchment locations). Gully erosion tends to be focused on soils derived from granite and sandstone rock types, in the drier and hillier grazing areas. At the regional scale, riverbank erosion is relatively minor, but can dominate in some catchments such as the Mary River (Fig. 2d). There has been major river erosion in that catchment from clearing of riparian vegetation and extraction on the riverbed in contrast to relatively low rates of hillslope and gully erosion.

Coastal areas with high sediment yields are dominated by hillslope erosion, but inland where the hillslope erosion rate is lower, channel erosion processes can dominate (Fig. 3a). For many areas both channel and hillslope sediment sources are important. Fig. 3a and the sediment budget both show that to model only hillslope erosion would lead to quite an incomplete picture of sediment sources in the region.

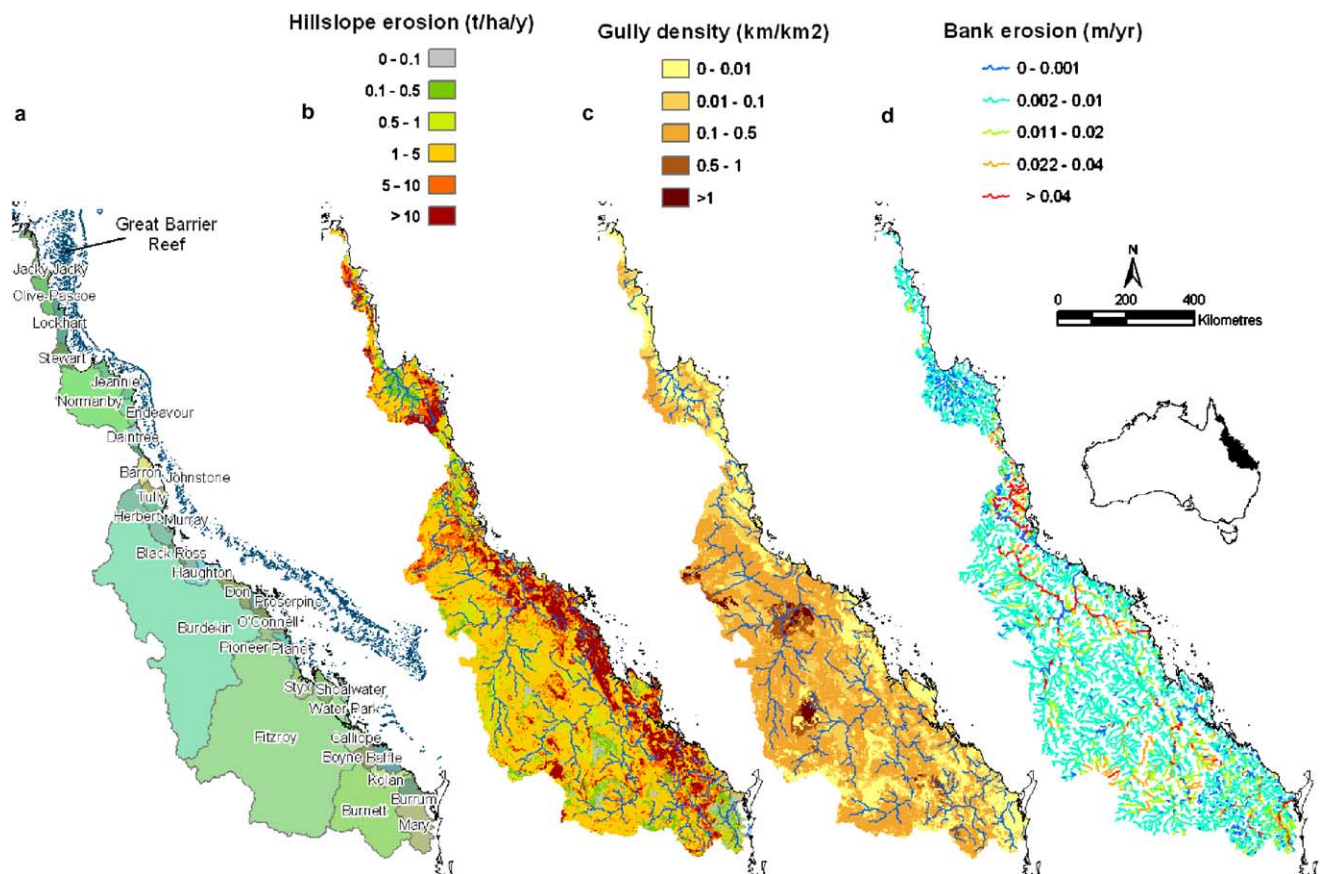


Fig. 2. (a) Great Barrier Reef and catchment, (b) predicted pattern of hillslope erosion, (c) predicted pattern of gully erosion, and (d) predicted pattern of riverbank erosion.

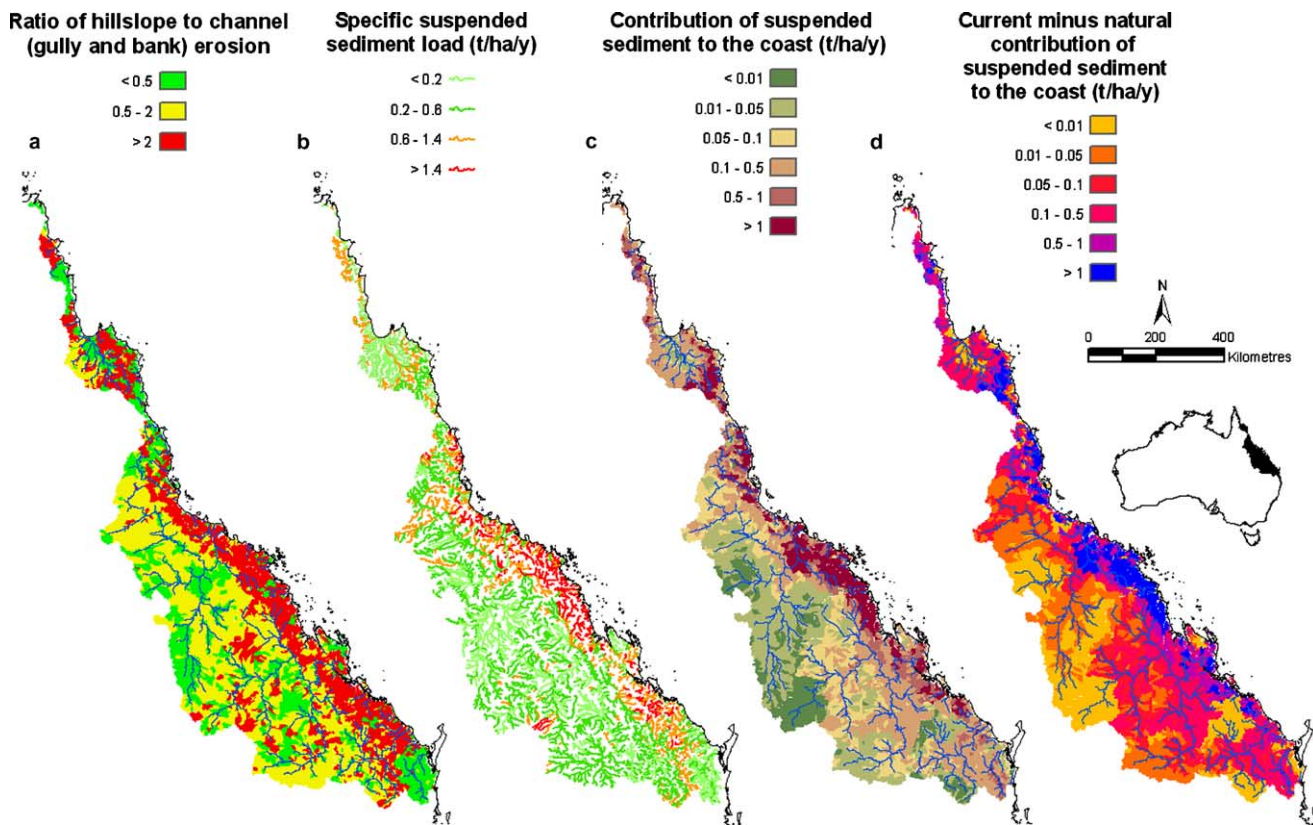


Fig. 3. (a) Estimated ratio of hillslope erosion to channel erosion (gully plus riverbank) in each sub-catchment of the GBR, (b) predicted specific suspended sediment load, (c) predicted contribution of suspended sediment to the coast under current conditions, and (d) the difference between estimated current and natural contribution to suspended sediment export.

3.2. River sediment loads

Sediment sources are only translated to downstream impacts if the eroded sediment is transported along the river network. The modelled sediment budgets for the region predict that approximately 40% of the total sediment delivered to streams is exported to the coast, and 47% of suspended sediment supplied is exported (Table 1). The rest is stored on floodplains or, in the case of bedload, on river beds, with some storage also occurring in reservoirs. There are highly varied patterns of deposition, with confined, high energy rivers being efficient conduits to the coast, while those with low energy floodplains may have large amounts of deposition which strongly reduce the amount of sediment reaching the coast. Approximately half the suspended sediment delivered to streams is deposited, and the deposition rates are in accordance with observations. Over 90% of floodplains are predicted to accumulate sediment at a rate of less than 2 mm/y or 2 m over 1000 years, with the bulk of them predicted to accumulate less than 1 m in 1000 years under the current rates of increased sediment supply. The vast bulk of coastal floodplains along the eastern Australia coast have formed in the last 10,000 years (Nanson, 1986). Similarly, while reservoirs are predicted to trap all but the finest sediment, they are not

predicted to fill for up to 1000 y, consistent with measurements of reservoir sedimentation (Outhet, 1991).

Patterns of area-specific suspended sediment load show the intensity of sediment transport in each river link. Area-specific sediment load is the mean annual sediment load divided by the upstream catchment area. The total predicted mean annual SS export to the sea is 16 Mt/y, which equates to a mean specific sediment yield of 0.4 t/ha/y. The highest specific sediment loads are in coastal areas from the Plane River north to the Johnstone River, and the Calliope, Boyne, Baffle Rivers (Fig. 3b). These are all small catchments where hillslope erosion dominates and where there is little opportunity for deposition. Inland there are strong patterns too, with the southern half of the Burdekin catchment having lower loads than the northern half (Fig. 3b). This is a result of both lower erosion and greater opportunities for deposition on extensive lowland floodplains. In some rivers, area specific sediment load decreases downstream, as a result of deposition and “dilution” from tributaries with relatively little erosion.

Sediment exports to the GBR are commonly summarised by Australian Water Resources Council River Basins. Total sediment export is dominated by the Fitzroy and Burdekin rivers, largely because they drain the largest areas (Fig. 4a). Examining area specific sediment

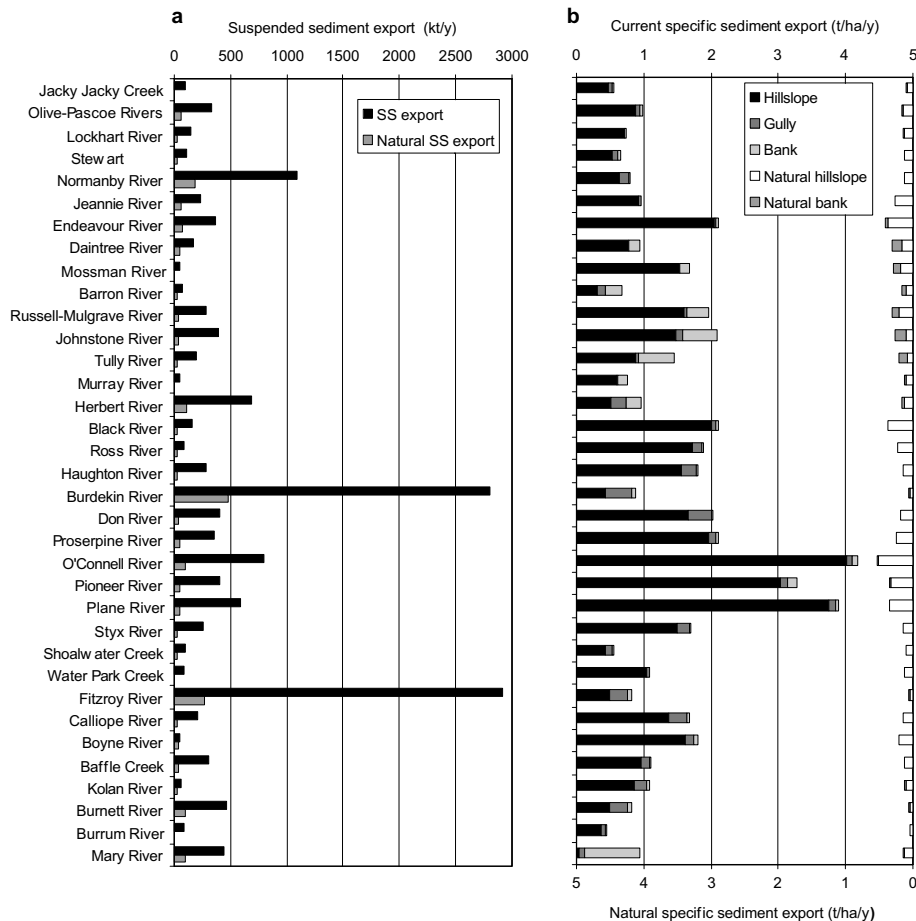


Fig. 4. (a) Predicted suspended sediment exports by AWRC basin under current and natural vegetation cover, and (b) specific sediment export by source for each AWRC basin under current and natural vegetation cover.

yield shows significant erosion and/or effective sediment delivery across the Mackay-Whitsundays (O'Connell, Pioneer and Plane River basins) and Wet Tropics river basins (Russell-Mulgrave, Johnstone, Tully River basins; Fig. 4b). The Burdekin and Fitzroy basins have low specific sediment exports because of the very large catchment size with extensive areas of low erosion and significant deposition. This illustrates the limits of these basin summaries, for there are areas of high contribution to export in those large catchments.

3.3. Sources of exported sediment

The SedNet model can map the sources of suspended sediment export to the coast by working up through the links in the river network, tracing in the model from where the sediment originated. The probability of sediment passing through an individual river link (i) is the ratio of the sediment yield from the link (Y_i) to the total sediment input to the link (S_i). The remaining sediment is lost to deposition. The contribution to coastal export from a sub-catchment (C_i ; t/y) is the sediment supply rate from that internal catchment (hillslope, gully and

riverbank erosion; E_i ; t/y) multiplied by the probability of that sediment passing through all river links, n on route to the coast;

$$C_i = E_i \prod_{i=1}^n \left(\frac{Y_i}{S_i} \right)$$

If the probabilities of sediment passing through a link are all equal then contribution to export is proportional to distance from the coast and sub-catchment sediment supply. Probabilities are not equal however, because deposition varies markedly through a river network.

The map of sub-catchment contribution to coastal export along the GBR coast (Fig. 3c) shows that overall 70% of the sediment comes from just 20% of the total catchment area. The areas of high contribution are all close to the coast. These sub-catchments are more likely to contribute because of the limited possibilities for sediment to be deposited between the source and coast and the high erosion in those areas. These are the small river basins with high area specific sediment loads, but also the coastal parts of the larger river basins, such as the Bowen River tributary of the Burdekin River. Some

inland areas are moderate contributors of sediment to the coast, while others have low delivery potential.

Identification of areas contributing large quantities of sediment to the coast must be placed in the context of natural sediment contributions that occur under natural vegetation cover and runoff. Almost all areas of current high contribution of sediment export have rates well above the predicted natural contribution (Fig. 3d). Some moderate contributions, such as north of the Endeavour basin, are largely natural sources.

Areas of unnaturally high contribution of sediment to the coast are where management to reduce erosion can most effectively reduce impact on the marine environment. The mapping of sediment sources identifies the type of erosion that is most responsible for sediment export from each contributing sub-catchment.

Overall the results show a highly skewed distribution of contributions to export. This suggests that the aims of the RWQPP (Anon, 2003) are achievable with the limited resources available if rehabilitation efforts are focussed on the areas that have a significantly accelerated contribution to export. This is a much more manageable problem than tackling erosion across the whole 423,000 km² catchment area to the GBR. It is only by mapping the terms of the sediment budget, that the contributing sources can be identified.

3.4. Comparison of exports to other studies

Previously published estimates of mean annual sediment export vary between 10 and 30 Mt/y (Table 2; excluding Furnas and Mitchell, 2001). This illustrates the uncertainties involved in all prediction methods. There is little difference between the estimate of Furnas (2003), based on the most comprehensive monitoring, and the current SedNet results, considering the considerable uncertainties in both methods, and high variability from one river basin to another. The estimate from this project is approximately 20% higher than that produced for the NLWRA, using essentially the same model, dem-

onstrating the uncertainties produced by the quality of input data that is available.

The assessment for this project predicts an eightfold increase in current sediment loads above natural rates, whereas most other studies that have attempted to assess this have predicted increases of approximately fourfold. Until recently all estimates of increases relative to natural load have been highly speculative and untested. Now, isotope studies of coral cores put historical river loads in a firmer long-term context. Corals beyond the mouth of the Burdekin River record a 5–10 times increase in sediment loads in historical times (McCulloch et al., 2003) similar to the sixfold increase predicted by SedNet for that river.

Of more interest than the total export, is the pattern of export between river basins, as this is how areas of concern are identified at the coarsest level. Fig. 5 compares the SedNet predictions for each AWRC river basin to those of Furnas (2003). For the Normanby, Johnstone, Tully, Herbert, Burdekin and Fitzroy Rivers the estimates of Furnas (2003) are based on intensive sediment monitoring for periods of two to seven years. Furnas (2003) classifies the basins into wet and dry tropic types and uses the monitoring to calculate a flow-weighted mean sediment concentration for each type

Table 2

Comparison of previously modelled estimates of current and 1850 suspended sediment loads to the GBR lagoon with the current modelling

Model	Current sediment (Mt/y)	1850 sediment (Mt/y)
Belperio (1983)	27.4	
Moss et al. (1992)	15.3	3.8
Neil and Yu (1996)	28.0	7.4
Furnas and Mitchell (2001)	3.3–66	
Brodie and Furnas (2003)	14.4	4.0
Furnas (2003)	14.4	4.4
NLWRA (Prosser et al., 2001b)	13.6	
Current model	16	2

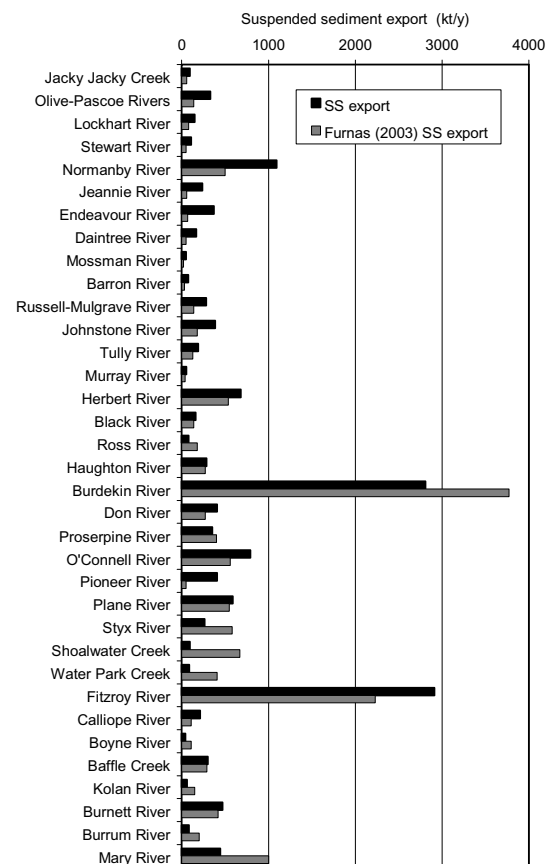


Fig. 5. Suspended sediment exports estimated by Furnas (2003) and the current SedNet predictions by AWRC basin.

of river. Loads in ungauged basins are then predicted from the mean concentration multiplied by mean annual discharge. The monitoring data does not include significant parts of the AWRC basin for the Normanby, Johnstone and Herbert, so Furnas (2003) scales the basin exports to include the unmonitored area.

Overall, there is relatively close agreement between SedNet and the more direct extrapolation of data by Furnas (2003). There are important differences between the two techniques however. For example, Furnas (2003) predicts that the Fitzroy River yields less sediment than the Burdekin River because it has a lower mean annual flow. In contrast we predict a higher sediment yield because of the greater amount of erosion in the catchment from more intensive land use and less extensive floodplains than in the southern Burdekin in particular. The Johnstone River is another area of difference, where SedNet predicts that the unmonitored part of the basin has more intensive erosion, because of highly erodible soils, than the monitored river. Our results in the monitored river agree well with the monitoring of Hunter and Walton (unpublished data). One of the largest differences between the two techniques is for the Normanby River, where monitoring has not included major floods but where the land use is not very intense, possibly leading to an overestimate from the SedNet model.

While such basin summaries are useful, many of the catchments are large and more detailed spatial information is needed to effectively target available funding. SedNet can provide this information. There is a need, however, to independently verify the spatial patterns of the model outcomes, not just the river exports. This has not been achieved for the GBR catchments, but SedNet has been applied to three catchments in other parts of Australia where geochemical tracing provides independent evidence of source areas and processes of erosion (e.g. Caitchoon et al., 2001; Olley et al., 2003; Wallbrink et al., 2003). In each case there is qualitative agreement of the dominant sediment source, in terms of particular sub-catchments and erosion processes.

3.5. Limitations of the modelling

The major limitations of the sediment budget approach are in our understanding of erosion and deposition processes at the large scale, and the availability of data to describe the patterns of those processes. SedNet is based on our current understanding of erosion processes, applied to the currently available data across the region. Several processes are poorly understood at the large scale, for example, floodplain deposition and bank erosion. There are no extensive data sets of spatial patterns in the world, let alone Australia, of either process. Consequently, constructing empirical rules of the driving environmental factors on each process, similar

to the RUSLE, is not possible. Thus, for the poorly known processes we have had to resort to physical reasoning. We have tried omitting the poorly understood terms from the budgets, or aspects of their control, such as riparian vegetation, but these lead to results that conflict with observations. To omit them would be to assume that the processes are not significant. We believe that the poorly defined rules bring more information than error to the budgets. The detailed spatial patterns of the sediment budgets remain speculative, and a better understanding of the most poorly understood erosion and deposition processes would improve confidence in the details of the model predictions.

While other transport processes are well described at small scales, this knowledge has not been expanded to larger scales. For example, the limitations of the RUSLE have been known for a long time. During this time there has been much research into the mechanics and modelling of soil erosion (e.g. GUEST: Misra and Rose, 1996; WEPP: Foster et al., 1995). The improved process knowledge has not been transferred effectively to improved large-scale prediction of soil erosion because of a lack of research into functions that relate the soil and hydrological parameters required in those models to available spatial information such as land use and soil type.

SedNet suffers from similar disadvantages to some degree, relying on intensive interrogation of spatial and hydrological data. Much of the effort in its application is in the data preparation. While the availability of spatial data has increased in recent years, it is of variable quality on a regional basis. High resolution datasets are available for some catchments (e.g. Herbert: Bartley et al., 2003), but for larger catchments, such as the Burdekin and Fitzroy, quality data is scarce. Better data, as well as process understanding, and transfer functions to relate the data to processes, are required for reliable prediction of detailed spatial patterns. Bank erosion prediction would benefit from better information on riparian condition and channel geometry for example.

An advantage of conceptual models such as SedNet is that, through sensitivity analysis, they offer a formal process for identifying the aspects of sediment transport and the controlling environmental variables that most matter at the large scale. The aim of SedNet is to encapsulate the most critical driving factors as well as possible with available knowledge, before moving on to secondary influences that refine predictions. At present, the 2 y flood is set as the discharge that overtops banks and initiates the possibility for floodplain deposition, but work is in progress to characterise patterns of channel geometry so that we can vary this factor spatially through catchments.

Mean annual sediment loads are predicted by SedNet and this resolution is suitable for planning major changes to land use type and practise. We need to

predict the response of sediment transport to the full range of hydrological conditions because managers are interested in long-term improvements to water quality and also because we have no way of predicting hydrological conditions of the next few years. SedNet approaches this problem by analysing the effects of 100 y of flow conditions in a probabilistic sense. That is, the mean annual loads include the varying intensity of processes integrated from low flows up to a 1:100 y event.

Daily sediment loads may be needed to examine ecological effects of water quality on rivers and estuaries. We believe this is best achieved by disaggregating the mean annual loads to a daily record of sediment loads or concentrations using a rating curve between concentration and flow based upon gauging records (e.g. DeRose et al., 2002). While such disaggregations are speculative beyond gauged conditions and may include extrapolation to ungauged catchments, we believe that they are preferable to attempts to model sediment budgets on daily time scales, which is well beyond current process understanding and data availability. For instance, distributed spatial patterns of daily discharge, let alone erosion, cannot be predicted with any accuracy in large catchments simply because of inadequate rainfall detection at that scale.

4. Conclusions

Spatial sediment budgets, routinely used as a research tool by geomorphologists, have much to offer for identifying sources of marine sediment pollution. We have applied the concept of sediment budgets to spatial modelling so that large areas, such as the GBR catchment, can be assessed relatively easily and repeatably. Importantly, the technique offers a predictive approach so that the consequences of future management can be predicted from changed budget inputs. The modelling approach of SedNet provides a conceptual basis for extrapolation of river loads to ungauged catchments based upon the effect of terrain, climate, hydrology, land use and soil type on sediment transport processes. While the technique requires considerable data analysis it has the advantage of making full use of these data to extrapolate patterns rather than more direct use of river gauging data, which often assumes that conditions are the same between gauged and ungauged basins.

Most significantly, the sediment budgets offer for the first time a means to identify the sources of exported sediment across the vast catchment area of the GBR, complementing the measurements of catchment exports. The budgets include gully and riverbank erosion, showing that these are locally significant sediment sources, in addition to hillslope erosion. The inclusion of deposition processes means that local sub-catchment erosion can be

separated from sediment that is transported all the way to the coast.

SedNet has been widely used in Australia by catchment managers to help prioritise and focus rehabilitation efforts. The results suggest that 70% of the suspended sediment discharged to the GBR comes from only 20% of the catchment area. The limits to resources for rehabilitation require that they be focused on the sediment sources that directly threaten downstream ecological values and other assets, such as the Great Barrier Reef World Heritage Area. The model results can guide sub-catchment selection. They can also be used in risk assessments of threats to the Reef (Brodie et al., 2001; Devlin et al., 2003; Greiner et al., 2003), and analyses of the costs and benefits of various management approaches to reducing marine pollution.

Much uncertainty remains, however, in the detailed pattern of sediment sources because of our limited understanding of sediment transport processes at the large scale, the limited resolution of spatial data, and functions that relate erosion processes to that data. There is much scope for improved resolution of the model and for testing of the resulting spatial patterns. Such improvements are required in order to have confidence in the outcomes that can be achieved from the considerable investments that are being made to reduce sediment exports in the region. An analysis to estimate the likely error range of the export estimates from the modelling will be important so that the load estimates can be used more confidently in the water quality target setting process now underway across the GBR catchment.

Acknowledgments

This project was funded by Environment Australia, through the Natural Heritage Trust. Much of the data was provided by the Queensland Department of Natural Resources, Mines and Energy. We also acknowledge the assistance of Hua Lu (CSIRO Land and Water) for hillslope erosion analysis, Tristram Miller (CSIRO Land and Water) for technical support and Miles Furnas (AIMS) and Heather Hunter (DNRME) for suspended sediment data for GBR catchment rivers. The constructive comments of two anonymous reviewers are gratefully acknowledged.

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